

# Wide Field Infra-Red Survey Telescope (WFIRST) 2.4-meter Mission Study

D. Content<sup>\*a</sup>, K. Aaron<sup>b</sup>, L. Alplanalp<sup>c</sup>, K. Anderson<sup>b</sup>, R. Capps<sup>b</sup>, Z. Chang<sup>b</sup>, J. Dooley<sup>b</sup>, R. Eggerman<sup>c</sup>, R. Goullioud<sup>b</sup>, D. Klein<sup>b</sup>, J. Kruk<sup>a</sup>, G. Kuan<sup>b</sup>, M. Melton<sup>a</sup>, J. Ruffa<sup>a</sup>, M. Underhill<sup>b</sup>, D. Van Buren<sup>b</sup>

<sup>a</sup>NASA Goddard Space Flight Center, Greenbelt MD

<sup>b</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA

<sup>c</sup>Exelis, Inc., Rochester, NY

## ABSTRACT

The most recent study of the Wide Field Infrared Survey Telescope (WFIRST) mission is based on reuse of an existing 2.4m telescope. This study was commissioned by NASA to examine the potential science return and cost effectiveness of WFIRST by using this significantly larger aperture telescope. We review the science program envisioned by the WFIRST 2012-2013 Science Definition Team (SDT), an overview of the mission concept, and the telescope design and status. Comparisons against the previous 1.3m and reduced cost 1.1m WFIRST design concepts are discussed. A significant departure from past point designs is the option for serviceability and the geostationary orbit location which enables servicing and replacement instrument insertion later during mission life. Other papers at this conference provide more in depth discussion of the wide field instrument and the optional exoplanet imaging coronagraph instrument.

## 1. INTRODUCTION

In mid-2012, NASA commissioned a study of the potential for accomplishing the goals of the astrophysics decadal-winning mission concept for the Wide Field Infra-Red Survey Telescope (WFIRST) using one of two 2.4m telescopes made available to NASA. We report on the hardware and mission operations concept that resulted from that study, done jointly by the WFIRST project office, telescope team, and coronagraph instrument team. The charter for this study was to examine the science potential, cost, and risks entailed in this approach, and to compare with prior mission studies and cost estimates. The science definition team<sup>1</sup> has reported (in April 2013) a positive response<sup>2</sup> to the ability to accomplish the WFIRST science goals, plus much more. NASA has decided to continue to study this mission concept as the leading potential application of the first of these two telescope systems, with a programmatic start in the next few years.

The study was only 6 months duration, with a HQ-selected science definition team (SDT) and charter. Highlights of the charter include:

- Develop a DRM (Design Reference Mission) using one of the telescope assets, for a 2022 launch; keep cost comparable while achieving all or part of the science priorities for WFIRST
- Study science potential and rough cost and risk of adding an optional exoplanet imaging coronagraph instrument
- Rapid 6 month study time frame, with a report by April 30, 2013
- Compare science return to DRM1/2 [2012 study]<sup>3</sup>
- Study options to include:

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\* [David.content@nasa.gov](mailto:David.content@nasa.gov); phone 1 301 286-7382

- Observatory and mission concept to be compatible with on-orbit replacement of spacecraft and instrument modules;
- High orbit (Geosynchronous or high earth orbit/HEO)
- Optical communication

The executive summary of the report<sup>3</sup> summarizes the science potential of the mission concept that was reported out. The basic science questions that can be addressed are at the forefront of astrophysics:

- What is dark energy?
- Is our solar system special?
- Are the planets around nearby stars like those of our own solar system?
- How do galaxies form and evolve?

Also worth mentioning is the publication of a short version of the science case produced by the SDT, intended to be a science highlights writeup more accessible than the full report<sup>4</sup>. The recommended mission carries out much more than just the WFIRST science program (the top ranked new space mission priority in the astrophysics decadal review). Compared to the prior mission concepts' telescope apertures, 1.3m for DRM1 and 1.1m for DRM2, the larger 2.4m current telescope aperture enables astronomers to also make important contributions towards many of the enduring questions listed in the decadal survey. If equipped with an (optional) exoplanet imaging coronagraph instrument, WFIRST-2.4 can image Jupiter- and Saturn-like planets around the nearest stars. With this demonstration of exoplanet coronagraph technology, WFIRST-2.4 could be an essential stepping stone towards finding signs of life around nearby planets.

The baseline WFIRST science recommended by New Worlds, New Horizons decadal review includes an exoplanet census via exoplanet microlensing, an IR wide area survey, and a dark energy survey comprising both imaging (for SN detection, gravitational weak lensing, and galaxy astrometry) and spectroscopy (for supernova type 1a (SN1a) spectrophotometry and the galaxy redshift survey (GRS) used for both baryon acoustic oscillations and a redshift space distortion survey).

The optional coronagraph instrument was also studied; other reports at this conference will give more detail<sup>5-8</sup>.

Additionally, the strawman science plan allocates a higher proportion (25%) of the observing time for a general observer (GO) program. While this program is not allowed to increase the hardware requirements, the base capability of a very wide field instrumented field of view, capable of imaging and slitless spectroscopy, allows for much faster and deeper area surveys than prior missions. To help bring out the science potential, the SDT solicited one page straw man GO concepts from the astrophysics observer community and included approximately 50 of these as an appendix in the final report.

This paper introduces the baseline mission design and capabilities, working from a mission overview, to an overview of the space observatory and brief discussions of the telescope and the wide field and coronagraph instruments. A brief discussion shows that scheduling the required observations is possible and briefly introduces concepts of operations. Other contributions at this conference will go into more detail on each instrument (see<sup>5-8</sup> for coronagraph work and<sup>9</sup> for the wide field instrument).

## 2. OBSERVATORY OVERVIEW

The WFIRST-2.4 DRM uses the existing 2.4-meter telescope hardware, along with heritage instrument, spacecraft, and ground system architectures and hardware to meet the WFIRST-2.4 science requirements. The WFIRST-2.4 DRM baseline payload (wide field instrument and telescope) provides the wide-field imaging and slitless spectroscopy capability required to perform the Dark Energy, Exoplanet Microlensing, and near infrared (NIR) surveys and an optional coronagraph instrument supports the Exoplanet Coronagraphy science (see Fig. 1 for a fields of view layout).

The payload features a 2.4-meter aperture, obscured telescope, which feeds two different instrument volumes containing the wide-field instrument and the optional coronagraph (see Fig. 2 for an observatory optical block diagram). The

telescope hardware was built by ITT/Exelis and is being made available to NASA. This existing hardware significantly reduces the development risk of the WFIRST-2.4 payload.

The wide-field instrument includes two channels, a wide-field channel and an integral field unit (IFU) spectrograph channel. The wide-field channel includes three mirrors (two folds and a tertiary) and a filter/grism wheel to provide an imaging mode covering 0.76 – 2.0  $\mu\text{m}$  and a spectroscopy mode covering 1.35 – 1.95  $\mu\text{m}$ . The wide-field focal plane uses 2.1  $\mu\text{m}$  long-wavelength cutoff 4k x 4k HgCdTe detectors. The HgCdTe detectors are arranged in a 6x3 array, providing an active area of 0.281  $\text{deg}^2$ . The IFU channel uses an image slicer and spectrograph to provide individual spectra of each 0.15" wide slice covering the 0.6 – 2.0  $\mu\text{m}$  spectral range over a 3.00 x 3.15 arcsec field. The instrument provides a sharp point spread function (PSF), precision photometry, and stable observations for implementing the WFIRST-2.4 science.

The coronagraph instrument includes an imaging mode, an integral field spectrograph, and a low order wavefront sensor to perform exoplanet detection and characterization. The coronagraph covers a spectral range of 0.4 – 1.0  $\mu\text{m}$ , providing a contrast of  $10^{-9}$  with an inner working angle of  $3\lambda/D$  at 400 nm.

The SDT considered both geosynchronous and Sun-Earth L2 (2<sup>nd</sup> Lagrange point, further from the sun than the Earth) orbit options and selected a 28.5° inclined, geosynchronous orbit as the baseline for this study. The primary factor that drove the selection of this orbit is the ability to continuously downlink data to the ground and obtain a much higher science data rate (See Table 1). The SDT weighed these benefits against the higher radiation environment and slightly less stable thermal environment versus the Sun-Earth L2 orbit chosen by the previous WFIRST SDT. Preliminary radiation analysis was performed during this study to assess the impact of the electron flux environment on the HgCdTe detectors. The analysis shows that a three-layer sandwich of graphite epoxy and lead can reduce the event rate in the detectors caused by trapped electrons to a level below that of Galactic cosmic rays. Preliminary thermal analysis shows that the HgCdTe

Channel field layout for AFTA-WFIRST

6x3 H4RG @ 0.11"/p, 0.328 sq.deg

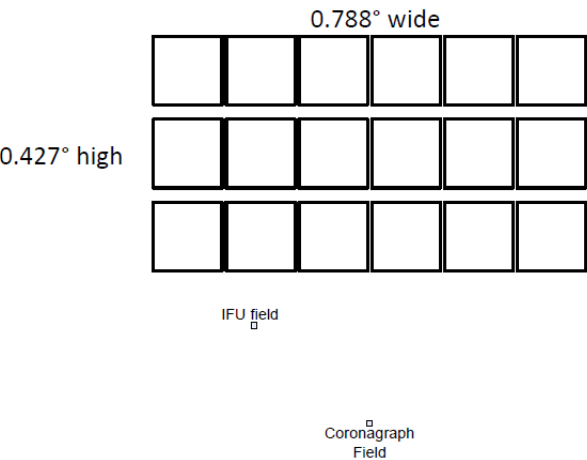


Figure 1: The WFIRST-2.4 instrument field layout, as projected on the sky, showing the wide-field instrument (including the IFU) and the optional exoplanet imaging coronagraph.

Parameter	Geosynchronous Orbit	Sun-Earth L2	Comment / Impact
Telescope operating temperature	Limited by optomechanics	Limited by optomechanics	Long wavelength limit (2 $\mu\text{m}$ ) is independent of Geo / L2 orbit
Telemetry Downlink Rate	>1 Gbps	Low	Geo allows more data down and continuous downlink
Radiation	p+ and e-	p+ only	Geo requires significant shielding of the focal plane
Viewing constraints	Moderate: Bulge, eclipses	Small	Geo constraints reduce efficiency but are tolerable

Table 1: Orbit trade considerations.

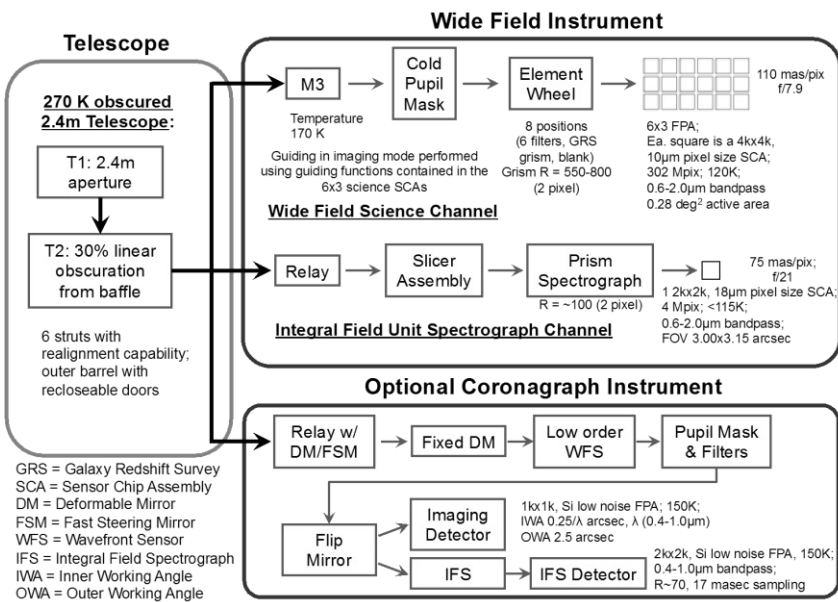


Figure 2: WFIRST-2.4 payload optical block diagram.

detectors can be held passively at 120K while meeting the thermal stability requirements in the selected orbit.

An Atlas V 541 launch vehicle will inject the observatory into a geosynchronous transfer orbit. Using a bi-propellant propulsion system, the spacecraft will circularize the geosynchronous orbit at an inclination of 28.5°. The mission life is 5 years (6 years with the optional coronagraph) with consumables sized to allow an extension for a total of 10 years. The spacecraft uses mature technology and redundant hardware to protect against any one failure prematurely ending the mission. It provides a fixed solar array/sunshield that allows operations over the full field of regard.

The SDT charter specified that the WFIRST-2.4 observatory be serviceable. For this study, it was decided to provide servicing at a module level, i.e. an entire instrument or a spacecraft module containing multiple electronics boxes. The modularity will also be a benefit during integration and test of the observatory. On the payload side, an instrument carrier was designed to attach to the existing telescope metering structure interfaces and provide volumes for two instrument modules. The instrument carrier interfaces the instrument modules to the carrier. The carrier provides mechanical latches (with design heritage from the Hubble Space Telescope (HST)), contains harness to route power and data between the spacecraft and the instrument modules, and provides thermal isolation between the two instrument volumes. Figure 3 shows an overall observatory view.

2.1. Observing Program

Table 2 presents the baseline observing program. Here we describe the various science measurements and mission concept that enables them. It should be emphasized that many if not all of the measurements are strongly enhanced by the improvements in both collecting area and angular resolution afforded by the reuse of the existing telescope system.

2.1.1 Widefield Instrument Observing Program

High-accuracy pointing, knowledge, and stability are all required to resolve galaxy shapes and precisely revisit both the microlensing and SN fields and support coronagraphy. Pointing to between 54° and 126° off the Sun enables the observation of exoplanet microlensing fields for up to 72 continuous days during each of the twice yearly Galactic Bulge viewing seasons.

The microlensing survey requires large light gathering power (collecting effective area times field of view) for precise

Table 2: WFIRST-2.4 design reference mission observing program. The quoted magnitude/flux limits are for point sources, 5σ for imaging, 7σ for HLS spectroscopy.

WFIRST-2.4 Design Reference Mission Capabilities						
Imaging Capability	0.281 deg <sup>2</sup>		0.11 arcsec/pix		0.6 – 2.0 μm	
Filters	Z087	Y106	J129	H158	F184	W149
Wavelength (μm)	0.760-0.977	0.927-1.192	1.131-1.454	1.380-1.774	1.683-2.000	0.927-2.000
PSF EE50 (arcsec)	0.11	0.12	0.12	0.14	0.14	0.13
Spectroscopic Capability	Grism (0.281 deg <sup>2</sup> )			IFU (3.00 x 3.15 arcsec)		
	1.35 – 1.95 μm, R = 550-800			0.6 – 2.0 μm, R = ~100		
Baseline Survey Characteristics						
Survey	Bandpass	Area (deg <sup>2</sup> )	Depth	Duration	Cadence	
Exoplanet	Z, W	2.81	n/a	6 x 72 days	W: 15 min	
Microlensing					Z: 12 hrs	
HLS Imaging	Y, J, H, F184	2000	Y = 26.7, J = 26.9 H = 26.7, F184 = 26.2	1.3 years	n/a	
HLS Spectroscopy	1.35 – 1.95 μm	2000	0.5x10 <sup>-16</sup> ergs/cm <sup>2</sup> @ 1.65 μm	0.6 years	n/a	
SN Survey				0.5 years (in a 2-yr interval)	5 days	
	Wide	Y, J	27.44	Y = 27.1, J = 27.5		
	Medium	J, H	8.96	J = 27.6, H = 28.1		
	Deep	J, H	5.04	J = 29.3, H = 29.4		
IFU Spec	7 exposures with S/N=3/pix, 1 near peak with S/N=10/pix, 1 post-SN reference with S/N=6/pix Parallel imaging during deep tier IFU spectroscopy: Z, Y, J, H ~29.5, F184 ~29.0					
Guest Observer Capabilities						
1.4 years of the 5 year prime mission						
	Z087	Y106	J129	H158	F184	W149
Imaging depth in 1000 seconds (m <sub>AB</sub> )	27.15	27.13	27.14	27.12	26.15	27.67
t <sub>exp</sub> for C <sub>read</sub> = C <sub>sky</sub> (secs)	200	190	180	180	240	90
Grism depth in 1000 sec	S/N=10 per R=600 element at AB=20.4 (1.45 μm) or 20.5 (1.75 μm) t <sub>exp</sub> for C <sub>read</sub> = C <sub>sky</sub> : 170 secs					
IFU depth in 1000 sec	S/N=10 per R=100 element at AB=24.2 (1.5 μm)					
Slew and settle time	chip gap step: 13 sec, full field step: 61 sec, 10 deg step: 178 sec					
Optional Coronagraph Capabilities						
1 year in addition to the 5-year primary mission, interspersed, for a 6-year total mission						
Field of view	Annular region around star, with 0.2 to 2.0 arcsec inner and outer radii					
Sensitivity	Able to detect gas-giant planets and bright debris disks at the 1 ppb brightness level					
Wavelength range	400 to 1000 nm					
Image mode	Images of full annular region with sequential 10% bandpass filters					
Spectroscopy mode	Spectra of full annular region with spectral resolution of 70					
Polarization mode	Imaging in 10% filters with full Stokes polarization					
Stretch goals	0.1 arcsec inner annulus radius, and super-Earth planets					

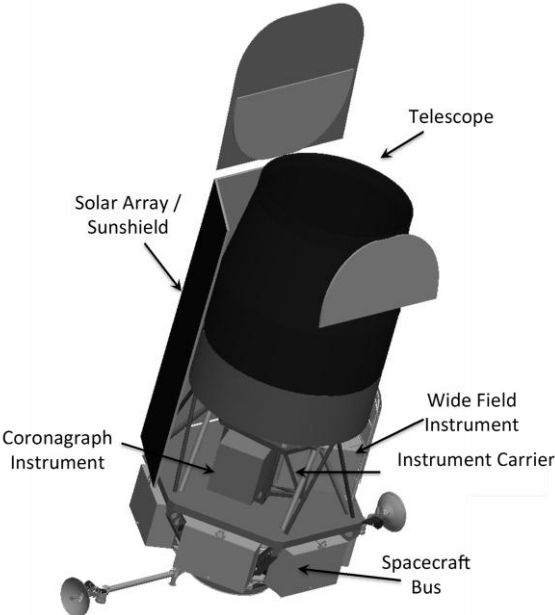


Figure 3: WFIRST-2.4 Observatory configuration featuring the 2.4m telescope, two modular instruments, and a modular spacecraft.

photometric observations of the Galactic Bulge to detect star and exoplanet microlensing events. Multiple fields are observed repeatedly to monitor light curves of the relatively frequent stellar microlensing events and the much rarer events that involve lensing by both a star and a planet. In the latter case, the planetary signal is briefly superposed on the stellar signal. Microlensing monitoring observations are performed in a wide filter spanning  $0.93 - 2.0 \mu\text{m}$ , interspersed ~twice/day with brief observations in a narrower filter for stellar type identification.

The GRS measurement requires near infrared (NIR) spectroscopy to centroid  $\text{H}\alpha$  emission lines and NIR imaging to locate the position of the galaxy image relative to the dispersion window. Dispersion at R 550-800 (2 pixels) enables centroiding the  $\text{H}\alpha$  emission lines to a precision consistent with the redshift accuracy requirement. To address completeness and confusion issues, grism observations over at least 3 roll angles, two of which are approximately opposed, are performed over ~90% of the mapped sky. The bandpass range of  $1.35 - 1.95 \mu\text{m}$  provides the required redshift range for  $\text{H}\alpha$  emitters.

The SN measurement also requires large light gathering power to perform the visible and NIR deep imaging and spectroscopy needed to identify, classify, and determine the redshift of large numbers of Type Ia SNe. Precise sampling (S/N of 15) of the light curve every five days meets the photometric accuracy requirement; the use of three NIR bands allows measurements of SNe in the range of  $0.4 < z < 1.7$ . The wide spectral range provides better control of systematic errors at low  $z$  than can be achieved by the ground and extends the measurements beyond the  $z \sim 0.8$  ground limit.

The WL measurement requires an imaging and photometric redshift (photo- $z$ ) survey of galaxies to mag AB  $\sim 24.6$ . A pixel scale of 0.11 arcseconds balances the need for a large field of view with the sampling needed to resolve galaxy shapes. Observations in three NIR filters, with  $\geq 5$  random dithers in each filter, are made to perform the required shape measurements to determine the shear due to lensing, while observations in an additional NIR filter are combined with color data from the shape bands and the ground to provide the required photo- $z$  determinations. The GRS grism and the IFU, along with overlapping ground observations, are used to perform the photo- $z$  calibration survey (PZCS) needed to meet the WL redshift accuracy requirement.

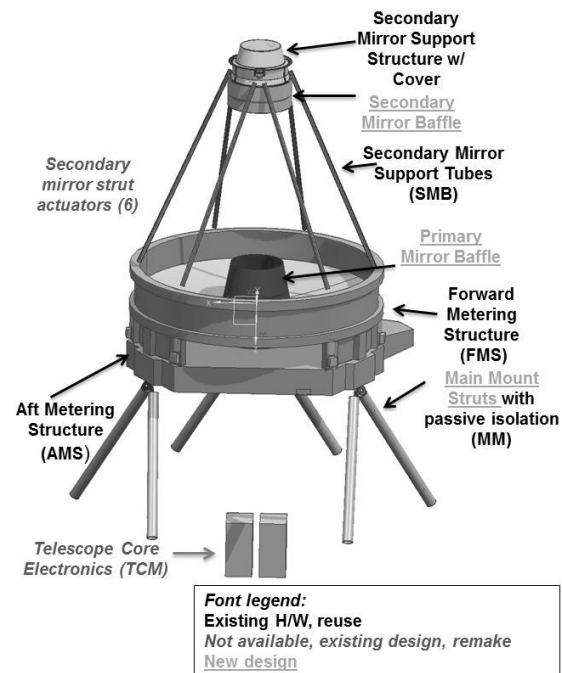
## 2.1.2 Coronagraph Observing Program

The coronagraphy measurements require imaging and spectroscopy to detect and characterize exoplanets. Coronagraphy requires high thermal stability of both the telescope and the coronagraph during observations. The relatively short initial observations focus on discovery of planets near the target star, while longer observations are required for planet spectroscopic characterization.

## 3. OBSERVATORY ELEMENTS

### 3.1. Telescope

The WFIRST-2.4 DRM is based on use of a repurposed, space flight qualified 2.4-meter, obscured two-mirror telescope (see Fig. 4). Repurposing modifications will include addition of a tertiary mirror (in the wide field instrument) to convert to a three mirror anastigmat (TMA) optical configuration to achieve a wide FOV capability, new internal stray light baffling optimized for the wide FOV, electronics replacements, new thermal blankets, and efforts to reach a slightly lower operating temperature than originally specified. The operating temperature will be 270 K, which enhances performance for infrared wavelengths out



**Figure 4: The telescope components without the outer barrel assembly (see Fig. 3).**

to 2.0  $\mu\text{m}$  while staying close to the original design specifications. The scientific advantage of this telescope is its much larger aperture relative to previous DRM concepts. The larger aperture increases both angular resolution and collecting area, allowing deeper and finer observations per unit observing time: The image is 1.9x sharper (the ratio of the PSF effective areas at H band, even after allowing for the centrally obscured aperture in the 2.4-m telescope). The fact that the majority of the hardware exists eliminates considerable cost, schedule and technical risk from the development program.

The telescope's pupil is obstructed by the secondary mirror baffle to a linear obscuration ratio of 30. The mounted secondary mirror has a 6 degree of freedom mechanism to adjust alignment on orbit, as well as a fine focus capability. The complete telescope includes an outer barrel assembly (OBA). The OBA provides a closed tube external light baffle, aperture doors, and telescope thermal isolation.

The telescope optics are made from ultra-low expansion material (Corning ULE<sup>®</sup>). The mirrors are significantly lightweighted and thermally stable. The telescope's structure is manufactured from mature low-moisture uptake composites to minimize mass and thermal distortions while providing superior stiffness and stability. The structure has active thermal control (heaters) and is isolated from the solar array by the OBA to minimize heat transfer into the telescope and instrument bay.

The two telescope mirrors feed both the wide field instrument<sup>9</sup> with a wide field of view channel and an integral field unit, and an optional nearly on-axis (in field) coronagraph instrument<sup>7</sup>. The most important performance requirement for the telescope to enable the WFIRST-2.4 science is stability. Based on the low expansion materials, the thermal design, and the active heater control, the wavefront stability delivered to the wide field imager is modeled to be  $<0.15$  nm rms over one 24-hour GEO orbit thermal cycle.

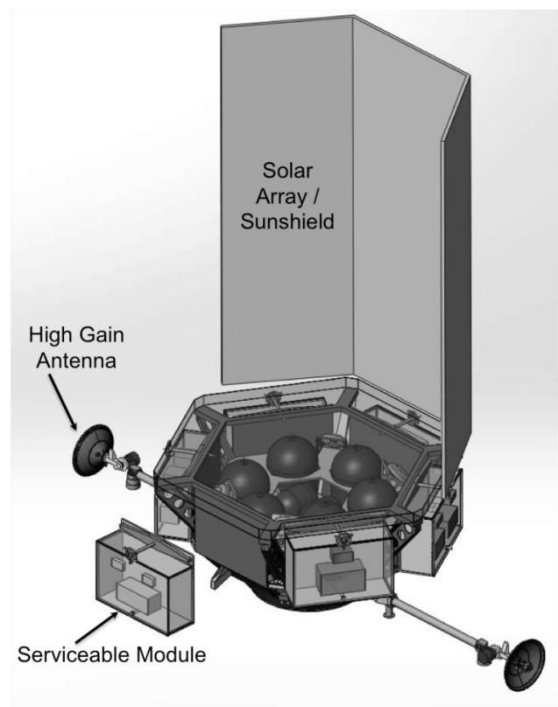
The telescope control electronics are located in a serviceable electronics module in the spacecraft and perform higher control functions such as commanding actuators and managing thermal set-points.

The cost, schedule, and technical risk associated with the telescope development have already been significantly mitigated; the telescope hardware and supporting GSE largely exists and spare parts are available for most of the components. New stray light baffles, thermal blankets, and electronics derived from commercial products are low risk modifications.

### 3.2. Spacecraft

The WFIRST-2.4 spacecraft has been designed to provide all the resources necessary to support the payload in geosynchronous orbit using mature and proven technology. The design is based on the Solar Dynamics Observatory (SDO) spacecraft, which was designed, manufactured, integrated, tested, and qualified at GSFC and is currently operating in geosynchronous orbit. The spacecraft bus design provides cross strapping and/or redundancy for a single-fault tolerant design. An isolated view of the spacecraft and solar array/sunshield structure is shown in Fig. 5.

**Structures and Thermal:** The spacecraft bus design features three decks stiffened by six gussets and faced with module support plates all composed of aluminum honeycomb panels



**Figure 5:** Spacecraft bus with solar array/sunshield showing serviceable modules with spacecraft and payload electronics. The top deck of the spacecraft is removed to allow viewing of the propulsive subsystem.

with M55J composite facesheets and sized to meet minimum launch vehicle frequency requirements. The spacecraft design features six serviceable modules containing spacecraft, instrument, or telescope electronics with the electronics arranged in functional subsystems. These modules are designed to be robotically serviceable, enabling refurbishment or upgrades to the observatory by replacing individual modules. Each module contains a set of connectors with alignment features to allow “blind mating” of the module harness connectors to connectors on the harness internal to the spacecraft bus connecting between modules and to the payload. This electrical interface has been demonstrated on the HST radial instruments. The spacecraft cold-biased thermal design maintains the spacecraft and payload electronics within their operational limits system using surface coatings, heaters, and radiators. The bus also supports a multi-panel fixed solar array/sunshield to prevent the Sun from illuminating instrument radiators during science observations at roll angles up to 15°.

**Electrical Power:** Three fixed, body-mounted solar array panels provide the observatory power. The solar array is sized to provide full observatory power at end of life with 2 strings failed at the worst case observing angles of 36° pitch and 15° roll with 30% power margin. The geosynchronous orbit has two eclipse seasons of ~23 days per year with a maximum eclipse period of 72 minutes. A 160 A-hr battery is sized to accommodate all observatory loads during the maximum eclipse duration.

**Communications:** The communication subsystem design leverages the SDO design to provide high reliability, continuous data downlink from the geosynchronous orbit. The high rate science downlink reuses the SDO design, using two dedicated Ka-band transmitters, each with a 0.75 m gimbaled antenna, to downlink science data at a rate of 150 Mbps without interrupting science operations.

**Command & Data Handling:** The observatory uses a MIL-STD-1553B command/telemetry bus and uses SpaceWire for the high rate science data. The C&DH provides the interface between the instrument high rate science data and the Ka-band system and formats and encodes the instrument science data for downlink. With both the wide-field and coronagraph instruments operating, the C&DH will interleave this data onto the Ka-band downlink. Due to the direct, continuous science data downlink, no science data recorder is required for WFIRST-2.4.

**Propulsion:** The propellant load provides a total delta V of ~1580 m/s (~1550 m/s for orbit circularization and ~30 m/s for station keeping, momentum management and disposal) and covers 3 $\sigma$  variations in launch vehicle performance, propulsion system performance, and flight dynamics errors. The propulsion subsystem control and safety inhibit electronics are contained in the Attitude Control Electronics box.

**Attitude Control:** The spacecraft is three-axis stabilized and uses data from the inertial reference unit, star trackers, and the payload fine guidance sensor (FGS) (function performed by the wide field instrument) to meet the coarse pointing control of 3 arcsec, the fine relative pointing control of 10 mas pitch/yaw and 1 arcsec roll, and stability of 20 mas pitch/yaw and 2 arcsec roll (all values RMS per axis). The internally redundant inertial reference unit provides precise rate measurements to support slew and settle operations. The star trackers (3 for 2 redundant) are mounted on the telescope aft metering structure, so they are directly related to the telescope pointing. The star trackers are used for coarsely pointing to within 3 arcsec RMS per axis of a target. After that, the FGS takes over to meet the fine pointing requirements for revisits and relative offsets. A set of four 75 N-m-s reaction wheels is used for slewing as well as momentum storage. The wheels are mechanically mounted to the propulsion support plate and passively thermally isolated from it to allow stable pointing at frequencies higher than the FGS control band.

### 3.3. Orbit

Several different orbit choices were considered for WFIRST-2.4 including geosynchronous Earth orbit, Sun-Earth L2, low Earth orbit, and highly elliptical Earth orbits. The best two options are Sun-Earth L2 and geosynchronous orbit.. We

have chosen to baseline a 28.5 deg inclined geosynchronous orbit with right ascension of the ascending node (RAAN) of 175 degrees and 105°W longitude, but have a mission architecture that works at Sun-Earth L2 as well. The geosynchronous orbit has the key advantage of continuous telemetry coverage with a single ground station. This enables a high data rate at low cost.

### 3.4. Optical Communications

The WFIRST-2.4 study team assessed the use of optical (laser) communications as a means of transmitting the science data to the ground. NASA is currently working on the Lunar Laser Communications Demonstration (LLCD), an optical communications demonstration on the LADEE mission, currently scheduled to launch in mid 2013. LLCD will demonstrate optical communications from lunar orbit at rates of 311 Mbps with pulse position modulation over ~16 hours in ~1 month of operations. NASA is also currently developing the Laser Communications Relay Demonstration (LCRD) as a hosted payload on a commercial communications satellite in geosynchronous orbit. The baselined data rate from geosynchronous orbit using DPSK modulation is 1.2 Gbps, but even higher data rates are expected.

The current WFIRST-2.4 Ka-band system downlinks data at a rate of 150 Mbps and is sufficient for the current DRM.

### 3.5. Concept of Operations

WFIRST-2.4 will support a wide range of science programs during its primary mission. Each of these programs has unique constraints involving the field of regard, cadence, and S/C roll angles. Moreover, observations in GEO are subject to viewing constraints on daily (motion around the Earth), monthly (Moon avoidance), yearly (Sun aspect angle), and secular (orbital precession) timescales. The SDT therefore constructed an existence proof of a possible observing plan, which showed that the strategic science programs are all mutually compatible, while simultaneously enabling a robust GO program. *This is only an existence proof: the actual observing plan will be updated depending on the needs of the dark energy and exoplanet communities and the highest-ranked GO programs.*

The “existence proof” observing plan was built according to the following constraints:

- **Mission duration:** The science phase of the primary mission is taken to last 5 years (or 6 years if the optional coronagraph is included). A notional penalty of 3.3% is applied for times when science observations are not possible (e.g. safe holds).
- **Orbit:** The initial orbit is a circular GEO with initial inclination of 28.5°, RAAN 175°, and centered at longitude 105°W, and is integrated including perturbations from the Sun, Moon, and non-spherical Earth. The initial RAAN was chosen to allow microlensing observations without daily interruptions throughout the primary mission despite the significant ( $-7^\circ/\text{yr}$ ) orbital precession. A larger value of initial RAAN would provide adequate visibility of the Galactic bulge but would have increased thermal loading from the Earth on the WFI radiator.
- **Viewing constraints:** The angle  $\epsilon$  between the line-of-sight and the Sun is constrained to 54—126°. The S/C roll angle relative to the Sun is constrained to  $\pm 15^\circ$  (for  $90 < \epsilon < 110^\circ$ ) or  $\pm 10^\circ$  (otherwise). The LOS cannot point within 30° of the limb of the Earth or Moon. During normal survey operations the WFI radiator normal is required to be kept at least 47.5° away from the Earth. An exception is made for the microlensing and SN programs that use an inertially fixed attitude throughout the orbit, where the radiator angle is allowed to be as low as 27° but only with a specific thermal load vs. time profile. Overheads between any two observations are computed based on the RW torque, angular momentum capacity, and settling and detector reset time.
- **High latitude survey:** The HLS provides 2 passes over the survey footprint in each of the 4 imaging filters and 4 passes with the grism, all at different roll angles and with small steps to cover chip gaps. The footprint is in regions of high Galactic latitude (to suppress extinction and confusion) and is contained within the planned LSST footprint. The grism has 2 “leading” passes (looking forward in Earth’s orbit) and 2 trailing passes to enable the single grism to rotate relative to the sky and provide counter-dispersion; the imaging mode has a leading and trailing pass in each filter.
- **Microlensing:** The microlensing program observes 10 fields in the Galactic bulge for continuous 72-day seasons, interrupted only by monthly lunar avoidance cutouts. The plan includes 6 seasons, including the first and last available season.
- **Supernovae:** The Type Ia supernova survey is carried out over 2 years; the duty cycle for actual observations (not including overheads) is 27%. The IFU observations, unlike the DRM1/2 slitless prism approach, do not have any roll angle constraints.
- **Guest observer program:** The GO program by definition cannot be “allocated” at this stage in the project. Moreover, in practice the planning of HLS observations will be re-organized based on the content of the GO program. For the purposes of the existence proof exercise, we have simply required that the time not used for other programs be  $\geq 1.25$  years, and that all portions

of the sky are visible in multiple years during otherwise-unallocated time. In computing the unallocated time, we subtract the penalty for a typical 90° slew from each unallocated window. (This way, the slewing penalty between any two programs is charged against the time allocation of one of the programs but not both.)

#### 4. SUMMARY

We have briefly described the science measurements, observatory configuration and concept of operations for the WFIRST-2.4 concept study. Other papers at this conference<sup>7,9</sup> provide more detail on each instrument.

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#### REFERENCES

- [1] Science Definition team, listed at [http://wfirst.gsfc.nasa.gov/science/sdt\\_public/sdt\\_membership.html](http://wfirst.gsfc.nasa.gov/science/sdt_public/sdt_membership.html).
- [2] Spergel, D., Gehrels, N., Breckinridge, J., Donahue, M., Dressler, A., et al., “Wide-Field InfraRed Survey Telescope-Astrophysics Focused Telescope Assets WFIRST-AFTA Final Report,” arXiv:1305.5422v2 [astro-ph.IM].
- [3] Green, J., et al., “Wide-Field InfraRed Survey Telescope (WFIRST) Final Report”, arXiv 1208.4012 (2012).
- [4] Weinberg, D., Gehrels, N., Breckinridge, J., Donahue, M., Dressler, A., et al., “WFIRST-2.4: What Every Astronomer Should Know,” arXiv:1305.5425[astro-ph.IM].
- [5] Carlotti, A., Kasdin, N. J., Vanderbei, R. J., “Shaped pupil coronagraphy with the AFTA telescope,” Proc. SPIE 8864-34 (2013).
- [6] Groff, T. D., Kasdin, N. J., Pueyo, L. A., Shaklan S., “Wavefront control scenarios for a coronagraph on the AFTA space telescope,” Proc. SPIE 8864-37 (2013).
- [7] Shaklan, S., Foote, M. C., Levine, M., Rodgers, J. M., Underhill, M., et al., “Coronagraph design for the AFTA telescope,” Proc. SPIE 8864-39 (2013).
- [8] Krist, J. E., Shaklan, S., Moody, D., “End-to-end optical modeling of potential coronagraphs for the AFTA space telescope,” Proc. SPIE 8864-64 (2013).
- [9] Content, D. A., Armani, N. V., Baker, C. L., Jackson, C. E., Kahle, D. M., et al., “Wide field instrument preliminary design for the wide field infrared survey telescope,” Proc. SPIE 8860-15 (2013).